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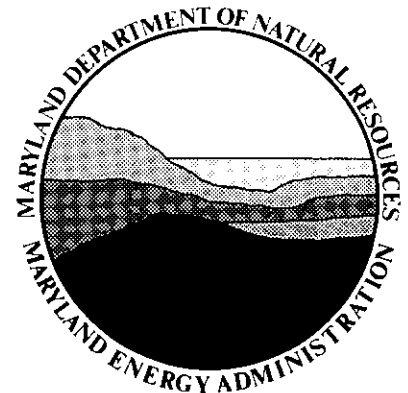
THE RELATIONSHIP BETWEEN PHOSPHORUS CYCLING
AND OXYGEN DEPLETION IN RESERVOIRS ON THE
LOWER SUSQUEHANNA RIVER

Prepared by

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July 1986

**MARYLAND POWER PLANT
RESEARCH PROGRAM**



As Secretary of the Maryland Department of Natural Resources, I am convinced that public support of DNR's mission is essential if we are to restore the State's once bountiful natural resources, especially the Chesapeake Bay, to the level which earned the title "America in Miniature." The information in this publication is designed to increase your understanding of our program and of Maryland's natural resources.

Torrey C. Brown, M.D.

UBLS-86-2

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FOREWORD

This final report, "The Relationship Between Phosphorus Cycling and Oxygen Depletion in Reservoirs on the Lower Susquehanna River" was prepared by Robert L. Dwyer of Martin Marietta Environmental Systems at the request of Michael Hirshfield of the Power Plant Research Program (PPRP), Maryland Department of Natural Resources (MDNR). This report documents the work done under Task CD-7 and CD-12 of PPRP Contract P20-83-03, and Tasks CD-11 and CD-12 of PPRP Contract P24-84-03. This final report is intended for publication by PPRP.

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ABSTRACT

The flux of water, sediment and nutrients in the lower Susquehanna River is controlled by four hydroelectric dams between Harrisburg, PA and the river mouth at Havre de Grace, MD. The detention of water in the reservoirs is accompanied by a degradation of water quality, especially severe reductions in dissolved oxygen (DO) concentrations. Conditions were worst in Conowingo Reservoir, the largest and furthest downstream of the four. Historical data indicated that reduced DO levels were associated with the uptake of phosphorus by phytoplankton. The present study utilized existing data from several sources, and a set of field surveys, to characterize the phosphorus dynamics within the reservoirs, to quantify the fluxes of phosphorus between reservoirs, and to determine relationships between phosphorus cycling and oxygen depletion. A series of simple phosphorus mass balance models were first developed from available data; the models were then subjected to flow analysis (derived from economic input-output analysis). The first set of flow analyses utilized data from a monitoring program (1971-1980) in Conowingo Reservoir to estimate the rates of phosphorus cycling and to define the eventual fates of phosphorus leaving the system. Results of 53 separate flow analyses of a five-compartment model of the reservoir showed that most of the phosphorus entering the reservoir was eventually deposited in the sediments, and less than half passed through a complete cycle within the ecosystem. However, the portion of phosphorus that was recycled through the decomposition of organic matter contributed to DO depletion, and was also made available for the fertilization of the primary production of organic matter. Decomposition of this organic matter caused additional DO consumption. The second set of flow analyses used data from intensive surveys in all four reservoirs during 1981, 1983 and 1984, resulting in 13- or 16-compartment flow analysis models of the ecosystems. Results showed that most of the phosphorus carried by the river at Harrisburg, PA was trapped by sedimentation in three of the four reservoirs downstream. As with the 53 Conowingo flow analyses, phosphorus remineralization rates provided realistic predictions of DO depletion. All of the flow analyses showed that phosphorus metabolism was a reasonable surrogate for oxygen metabolism. Phosphorus cycling was shown to make more phosphorus available to phytoplankton, so that additional organic matter was produced for eventual decomposition and oxygen consumption.

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I. INTRODUCTION

A. THE PROBLEM

The flow characteristics and water quality of the Susquehanna River south of Harrisburg, PA, are strongly influenced by the location and operation of four hydroelectric dams (Figs. I-1 and I-2). One characteristic associated with the dams and their reservoirs is the recurrence of periods of depletion of dissolved oxygen (DO). These anoxic periods occur regularly each summer, and are most severe in the two largest reservoirs-- Safe Harbor and Conowingo. Anoxia in the deep waters of the reservoirs is usually accompanied by hypoxic (severely undersaturated) conditions in the river reaches downstream of the hydroelectric turbine discharges. These hypoxic conditions have been associated with fish kills.

The Federal Energy Regulatory Commission (FERC) maintains jurisdiction over the licensing of hydroelectric plants. Because the four reservoirs on the lower Susquehanna River are located close together and could influence one another, FERC issued new, coterminous operating licenses for all four dams in August 1980. Each license contained an environmental article requiring the operating utility for each hydroelectric plant to undertake studies to resolve a number of outstanding environmental questions. Specifically, the objectives of the studies at each project, as defined by FERC, were to:

- Objective 1. Determine the seasonal variations of dissolved oxygen (DO) concentration and temperature in the project reservoir, in the discharge from the project, and in the Susquehanna River downstream [of the project].
- Objective 2. Determine the effects of project operation on temperature and DO levels in the reservoir, in the discharge of the project, and downstream [of the project].
- Objective 3. Determine the source, nature, and quantity of oxygen-demanding materials present in and entering the project reservoir.
- Objective 4. Determine the most feasible methods for ensuring that water released from the project meets State water quality standards.

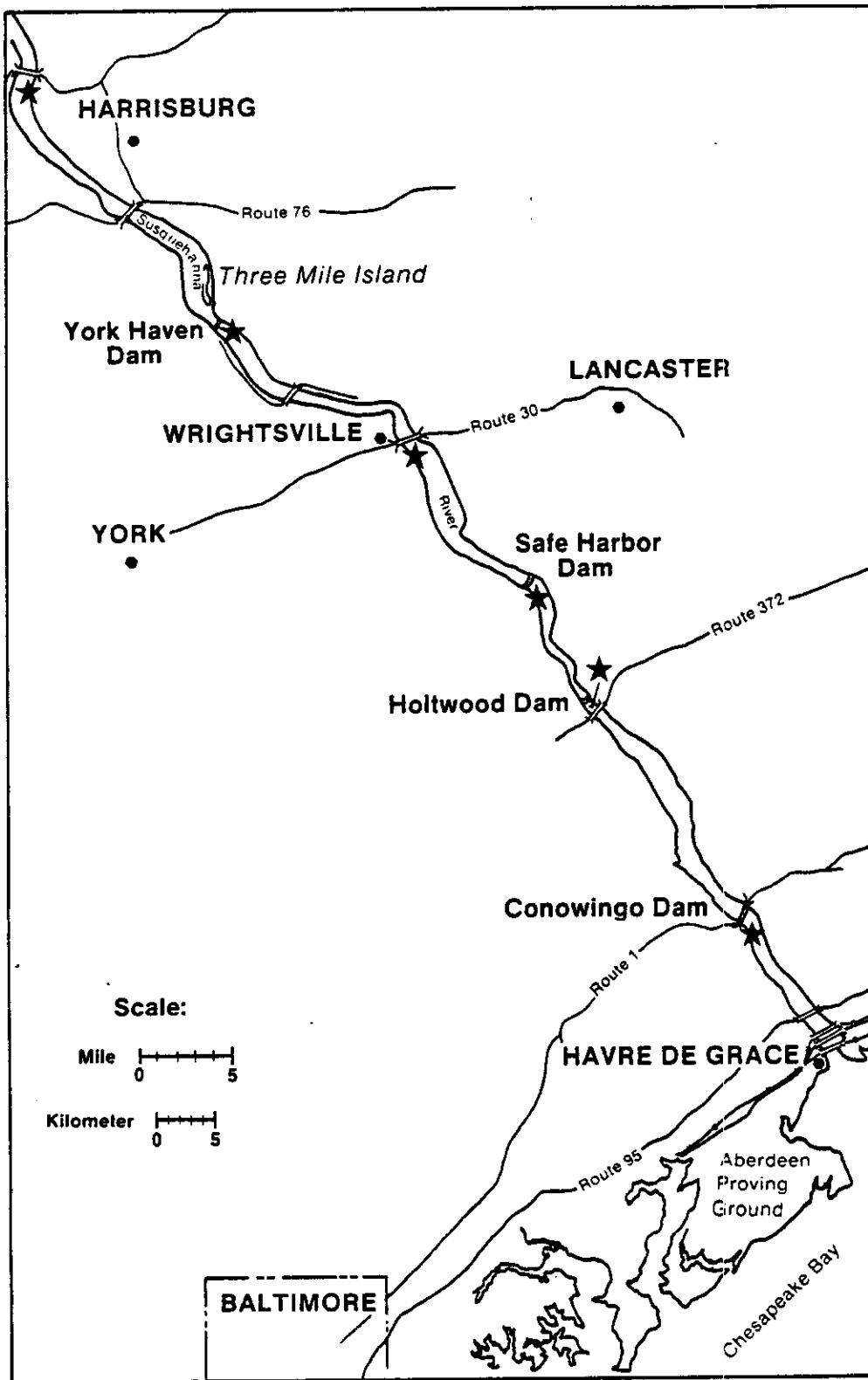


Figure I-1. Map of lower Susquehanna River between Harrisburg, PA, and Havre de Grace, MD. Locations of the four hydroelectric dams and two other boundary transects used in this study are shown.

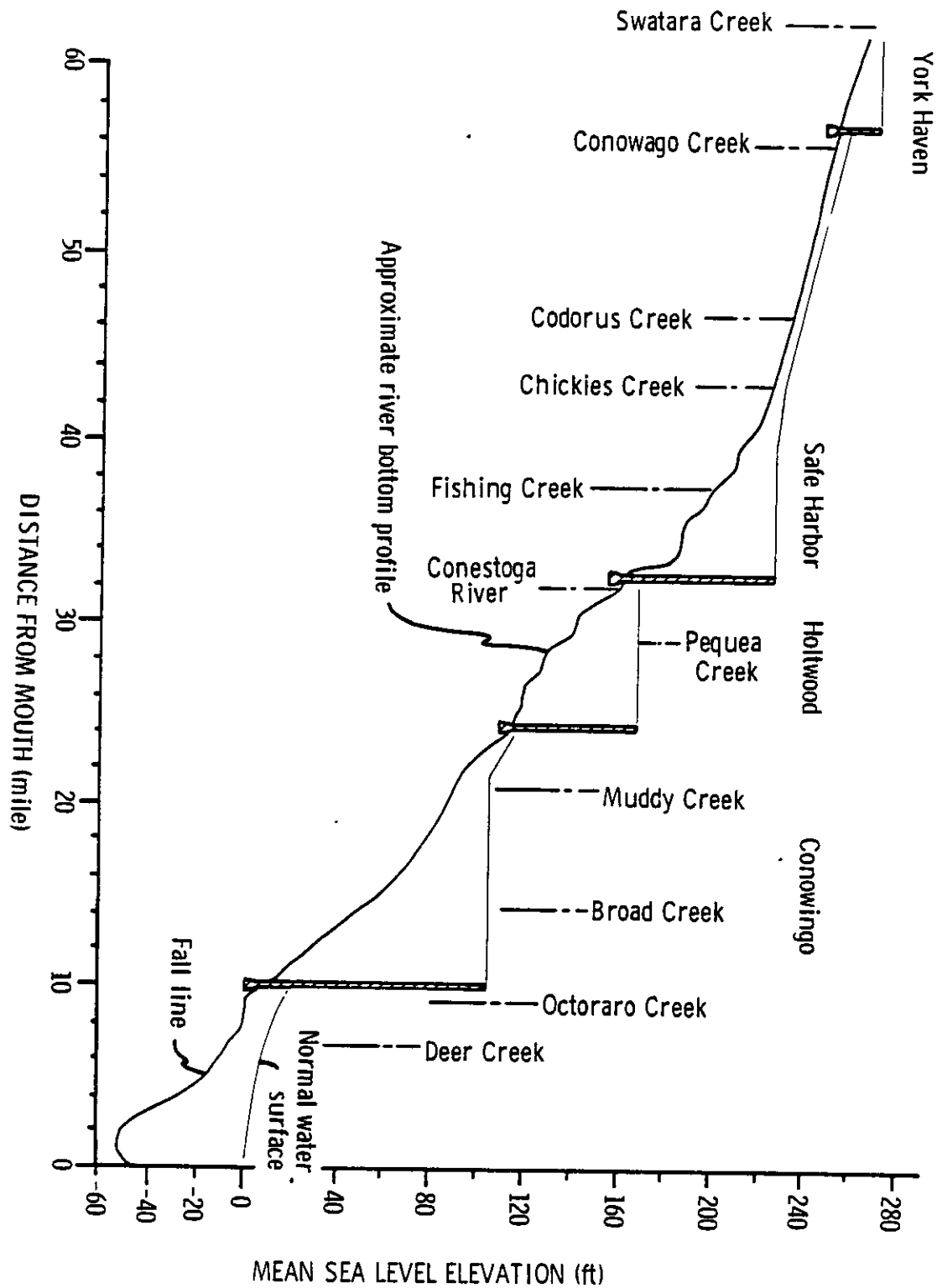


Figure I-2. Profile of water surface elevations and bottom elevations, corresponding to map of Figure I-1. Major tributaries are also shown.

- Objective 5. Determine minimum flow releases from the project that are necessary to protect and enhance fish and wildlife resources.

Objectives 1-3 were intended to define the frequency, severity, and causes of anoxic conditions. Objective 4 required the utilities to evaluate means of improving DO concentrations in the discharge of the plants. Finally, Objective 5 explicitly addressed the need to protect and enhance local fish resources by improving water quality or other habitat factors.

In response to Objectives 1-4, PPSP and the utility operating the Conowingo project (Philadelphia Electric Co. (PECO)) undertook a program of analyses of existing data and field measurements of the DO depletion problem in Conowingo Reservoir. This report describes the results of input-output analyses, sponsored by PPSP, to define important pathways, limiting nutrients, and sources and sinks for both internal cycling of materials and loadings coming from the upstream reservoirs that appeared to be related to oxygen consumption. A complementary PPSP-sponsored activity, the formulation of an ecosystem simulation model of Conowingo Reservoir (Summers 1985), defined the major processes of the seasonal DO cycle and provided a tool for testing various options for improving the DO concentration of the discharge (Objectives 2 and 4).

B. OBJECTIVES OF SPECIFIC ANALYSES

Three different sets of input-output analyses were performed as part of this study, each utilizing different data and addressing different specific objectives. The scopes of these input-output analyses were defined by the temporal and geographical extents of both the historical and newly-collected data. The following sections outline each of the analyses. In Chapter IV, all of the results are synthesized to develop overall conclusions about material dynamics in the river reach, and to identify factors that affect DO depletion. In addition, the results of these analyses are used to estimate the likelihood of success for management actions proposed for correcting the DO depletion problem in the system.

Analyses of Historical Data from Conowingo Reservoir

The DO depletion problem in the lower Susquehanna River is most severe in Conowingo Reservoir and in the downstream river reach directly influenced by the discharge of hypoxic water from this reservoir. The present analysis of the seasonal patterns and causes of DO depletion initially concentrated on Conowingo because of the severity of the problem there, and

because of Maryland's active involvement in the relicensing of the Conowingo Project. (The other three dams and reservoirs are in Pennsylvania.)

As part of the cooperative studies, PECO provided PPRP with data from an extensive monitoring program (1969-1981) for the Peach Bottom Atomic Power Station located on Conowingo Reservoir (Robbins and Mathur 1974; PECO unpublished). The data consist of biweekly or monthly measurements of DO, temperature, and concentrations of major water quality constituents at stations on the reservoir, as well as at its inflow and outflow. Preliminary data (Susquehanna River Basin Commission 1980) indicated that the decomposition of organic matter in the water column of the reservoir controlled the rate of DO consumption. The PECO historical data were sufficient to examine the relationships between the concentrations and loadings of various forms of organic material and resultant DO levels in the reservoir. Specifically, the analyses of the Conowingo historical data were used to:

- Define patterns of material (e.g., seston; phosphorus, whose cycling was closely related to that of oxygen) cycling in Conowingo Reservoir during 53 time intervals (ranging from days to weeks) from the summers of 1971 to 1980
- Examine the relationships of these cycling patterns to DO concentrations in Conowingo Reservoir.

Analyses of the Four-Reservoir System

Although this study initially focused on Conowingo, an examination of the historical data indicated that substantial loadings of particulate organic material were entering the reservoir from upstream (i.e., had passed through one or more of the three upstream reservoirs). Thus, an understanding of the relative importance of upstream vs. in situ sources for particulate organic matter was needed before strategies for improving the DO in Conowingo Reservoir could be formulated. Accordingly, the scope of this study was expanded to include the three upstream reservoirs.

Analyses of Data from Riverwide Surveys in August 1981

FERC had also recognized the possible dependence of the water quality of each of the projects on the ecosystem dynamics in any reservoirs upstream, so the licenses required that the studies at all four projects be coordinated. As a result of this coordination, water quality measurements were made at

three of the four reservoirs in the summer of 1981. This coordinated set of data facilitated an empirical analysis of the cumulative effect of these three projects on material cycling for the month of August 1981. Because of insufficient data (e.g., oxygen fluxes were not measured at reservoir boundaries, airwater diffusion could not be estimated precisely) a mass-balance for oxygen could not be formulated directly. Accordingly, phosphorus metabolism was used as a surrogate for oxygen metabolism.

Analyses of Data from Riverwide Surveys in 1983 and 1984

There was some concern that the inputs to the system and material fluxes between the reservoirs may not have been estimated consistently during the 1981 intensive field surveys because of the variety of organizations participating in the sampling. Also, none of the 1981 surveys attempted to estimate the sinking and deposition of seston, previously identified as a major sink for organic matter and particulate forms of nutrients. Accordingly, a series of surveys was designed and implemented to measure the fluxes of organic matter and nutrients under low vs. high river flow conditions:

- 5,000 cfs (19 September - 13 October 1983)
- 35,000 cfs (11-14 June 1984).

The surveys were conducted by Chesapeake Biological Laboratory (CBL); CBL's data report forms Appendix A of this report. The data from the two surveys were used to formulate two additional characterizations of material fluxes in the four-reservoir system (Chapter III). In addition, the CBL data also confirmed that phosphorus was the nutrient limiting primary production. The CBL data were also used to validate some of the phosphorus flows that had to be estimated in the input-output models of Conowingo Reservoir and the whole lower river system. Finally, results from all of the analyses are used to estimate the likelihood of success for management actions proposed for correcting the DO depletion problem in the system.

C. INPUT-OUTPUT ANALYSIS--BACKGROUND AND RATIONALE

In this report, a form of input-output analysis called flow analysis (Finn 1977) is used to quantify the transport, transformations, and fate of phosphorus in Conowingo Reservoir, as well as in the four-reservoir system. As discussed in the next section, phosphorus was identified as the nutrient limiting primary production. Primary production, in turn, is related to DO levels. Thus, phosphorus metabolism is a good surrogate for oxygen metabolism. Flow analysis is a relatively simple method

that uses the flows of a nutrient among the biotic and abiotic components of an ecosystem to derive indices of how the system functions.

Ecological flow analysis is based on economic input-output analysis (Leontief 1966). It was substantially modified for environmental applications by J. Finn (Finn 1976, 1977, 1980; Barber et al 1979), although parallel modifications of Leontief's input-output analysis for environmental applications were done by Hannon (1973, 1979) and Chen (1973). Input-output methods have been used to analyze carbon flow in four lake ecosystems (Richey et al. 1978; Lettenmaier and Richey 1978; Richey et al. 1982), to examine the effects of nitrogen fertilization on salt marsh nitrogen flows (Leschine and Smith 1978; Leschine 1979; Finn and Leschine 1980), and to characterize the habitats of the Mississippi Deltaic Plain and their vulnerability to resource development (Costanza et al. 1983).

Flow analysis takes a simpler, more empirical approach to defining system processes than does simulation modeling. The conceptual structure of the flow analyses model is based on Leontief's (1966) assumption about the flow of goods in economic systems: The total output of a system is the sum of the flow out of the system plus an amount of internal consumption that is proportional to system production. The initial conceptualization of an ecological flow model is based on physiological and ecological theory. As used here, the model structure is constrained by the amount and quality of data for defining material flows between the compartments. The model is largely independent of the assumptions needed to implement theoretical constructs for a particular situation (unlike the requirements of a mechanistic model). All one needs to know for a flow analysis are the flows into and out of each compartment of interest, the inflows and outflows between the outside world and each compartment, and any change in the storage of a compartment (e.g., the buildup or depletion of dissolved phosphorus in the water column). This total dependence on data means that the flow analysis model will allow inferences only about the present state of the system (no predictions or other extrapolations to conditions different from those used in model formulation are possible).

Most of the intercompartmental and external flow rates in the analyses in this report were derived directly from field measurements, although several flows that were not measured directly had to be estimated from the literature. The availability of several different sources of data, as well as the relative ease with which flow analysis models can be formulated and the associated calculations can be made, suggested that flow analysis models might be capable of defining the dynamics of oxygen-consuming materials in the system without the expense of developing a complex four-reservoir simulation model.

D. CONSTITUENTS CONTRIBUTING TO DO DEPLETION IN THE RESERVOIRS

In order to formulate flow analysis models capable of addressing the DO depletion problem, those constituents (e.g., seston, phytoplankton, nutrients) that directly affect DO levels and whose cycling patterns are related to the oxygen metabolism of the reservoir ecosystems must be defined.

The metabolism of the water column community dominates total oxygen dynamics in Conowingo Reservoir under summertime conditions; in particular, high rates of water column community respiration appear to be the major cause of the observed DO depletion (Sanders et al. 1982a, 1982b). Although the respiration of living phytoplankton contributes to the high rates of community respiration, phytoplankton biomass concentrations are rarely large enough to account for more than half of the total DO depletion. The majority of the DO depletion is associated with bacterial decomposition of organic matter. This organic material is both transported from upstream and produced by photosynthesis within Conowingo Reservoir. (A characterization of the reservoir ecosystems and estimates of some of the major environmental inputs are presented in Appendix B.)

The historical PECO data for Conowingo Reservoir indicate that local primary production is limited by the availability of phosphorus. During the summer N:P ratios (by weight) increase to 200:1 - 1,000:1, indicating a depletion of phosphorus relative to nitrogen. In order to identify possible relationships among phosphorus, phytoplankton, and dissolved oxygen, the data were screened using a correlation analysis. Specifically, monthly mean concentrations of available phosphorus, oxygen, and phytoplankton (measured as chlorophyll) in the surface (depths ≤ 6 m) and bottom (depths > 6 m) layers of the deep basin of the reservoir were subjected to correlation analyses (Table I-1). These preliminary correlations support the hypothesis that phosphorus is directly related to phytoplankton growth and perhaps to oxygen metabolism. Specifically, the correlation analyses indicated the following relationships:

- In surface waters, phytoplankton and phosphorus concentrations are negatively correlated, indicating that phosphorus is depleted as phytoplankton grow.
- Surface phytoplankton concentrations are negatively correlated with both surface and bottom DO concentrations, indicating that phytoplankton respiration or the decay of dead phytoplankton biomass contributes to DO depletion. (One would expect a positive correlation in surface waters if phytoplankton oxygen production contributed more oxygen than was consumed by respiration.)

Table I-1. Correlation matrix: monthly means of total phosphorus, phytoplankton, and dissolved oxygen in surface (≤ 6 m) and bottom (> 6 m) layers of Conowingo Reservoir (data from Robbins and Mathur 1974; and PECO unpublished). ("Total phosphorus" in their data are at concentrations much lower than needed to support the reported phytoplankton biomass; we have thus interpreted this constituent as "total dissolved phosphorus.")

	Surface (≤ 6 m)			Bottom (> 6 m)		
	Total Phosphorus	Phytoplankton	Dissolved Oxygen	Total Phosphorus	Phytoplankton	Dissolved Oxygen
<u>Surface</u>						
Total Phosphorus	1	-0.65(a)	0.74(b)	NS(c)	NS(c)	0.81(b)
Phytoplankton		1.0	-0.80(b)	NS(c)	0.75(b)	-0.81(b)
Dissolved Oxygen			1.0	NS(c)	-0.74(b)	-0.98(b)
<u>Bottom</u>						
Total Phosphorus				1.0	NS(c)	NS(c)
Phytoplankton					1.0	-0.66(a)
Dissolved Oxygen						1.0

(a) $P < 0.05$

(b) $P < 0.01$

(c) Nonsignificant

- Surface phosphorus is positively correlated with both surface and bottom oxygen concentrations, indicating that when phosphorus is depleted (e.g., by uptake by phytoplankton) oxygen also decreases.

Thus, phosphorus availability appears to influence the amount of locally-produced organic matter and, indirectly, DO concentrations in Conowingo Reservoir. Since phosphorus is both taken up during production and remineralized as a consequence of respiration and decomposition, it is a good indicator of total system metabolism. Estimation of a mass balance is easier

for phosphorus than for oxygen because phosphorus is not affected by processes that plague oxygen budget calculations (e.g., air-water exchange).

The correlation analyses were intended as a screening tool for developing hypotheses about the interrelationships among phosphorus, phytoplankton, and oxygen. The remainder of the analyses of this report were performed using historical PECO data, as well as more recent measurements, to quantify the relationship between phosphorus cycling and oxygen metabolism in Conowingo Reservoir and in the three reservoirs upstream.

Historically, data for the three upstream reservoirs are not extensive enough to permit such correlation analyses to confirm the phosphorus-DO relationship in those locations. However, data from the CBL seston surveys (Appendix A) confirm that phosphorus was limiting in all the reservoirs at the two river flows sampled (5,000 and 35,000 cfs).

In addition to phosphorus metabolism within the reservoirs, the loadings of dissolved phosphorus and particulate matter entering reservoirs from upstream also contribute to increased phosphorus cycling and DO depletion. These loading rates, and the residence times of various phosphorus forms within the reservoir (controlled by river flow), influence:

- Phosphorus dynamics within the ecosystem, including:
 - the uptake of dissolved phosphorus by phytoplankton
 - the remineralization of dissolved phosphorus through the decomposition of organic matter
 - the settling and burial of some organic material (with associated phosphorus) to the sediments
- Phosphorus fate, including:
 - the discharge of phosphorus in dissolved form, or particulate forms associated with particulate matter,

phytoplankton, and zooplankton, through Conowingo Dam to the upper Chesapeake Bay

-- the permanent burial in reservoir sediments.

Knowledge of the transformations and fate of phosphorus in Conowingo Reservoir and the three reservoirs upstream thus provides information on the processes that cause DO depletion.

II. METHODS

A. DERIVATION OF FLOW ANALYSIS EQUATIONS

The derivation of the mathematics of flow analysis is presented by Finn (1977). A summary of the derivation is presented here using Finn's notation. Flow analysis essentially reformulates an ecosystem's nutrient mass-balance within the framework of Leontief's (1966) input-output model. This model states that the total output of a system is the sum of the flow out of the system plus an amount of internal consumption that is assumed to be proportional to system production. To permit interpretation of the mathematical derivations of flow analysis, some notational conventions and terms must be defined:

a_{ij} = a scalar quantity, an element of a matrix

\underline{B} = a vector

\underline{C} = a matrix.

The total throughflow for compartment j (T_j) can be defined as internal consumption plus outflows (Fig. II-1):

$$T_j = \sum_{i=1}^n f_{ij} + y_j \quad (\text{II-1})$$

where

f_{ij} = an element of \underline{F} (a matrix of intercompartmental flows) representing the flow from compartment j to compartment i

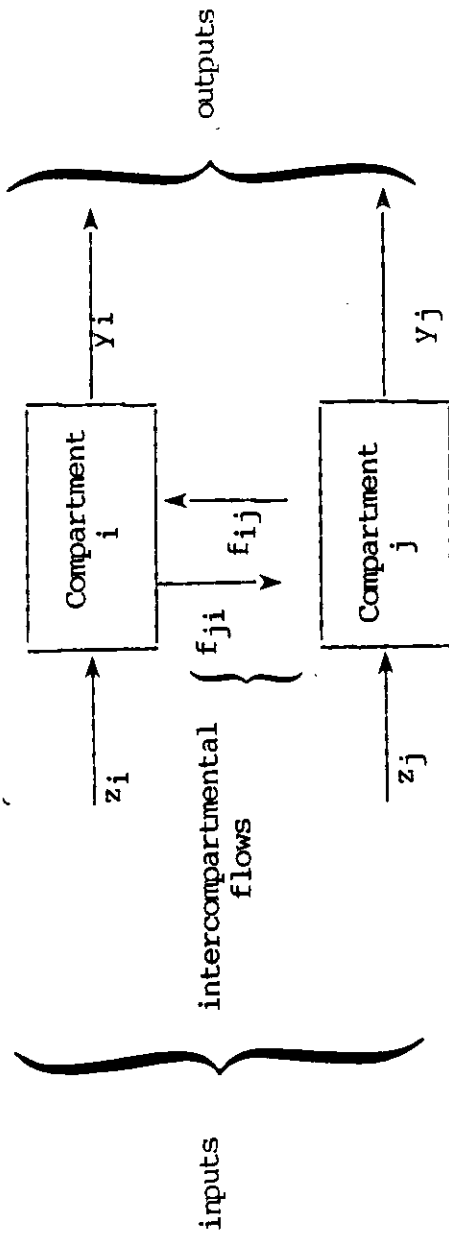
y_j = output from compartment j to the environment.

If the nutrient flow into a compartment is proportional to the production of the compartment (i.e., its total throughflow) then:

$$f_{ij} = q_{ij}^* T_i \quad (\text{II-2})$$

where

q_{ij}^* = an element of matrix \underline{Q}^* representing the portion of the throughflow of i that comes from j .



Outflow analysis:

$$T_i = f_{ji} + y_i = q_{ji}^* T_j + y_i$$

$$T_j = f_{ij} + y_j = q_{ij}^* T_i + y_j$$

or

$$\underline{T} = \underline{I} \underline{F} + \underline{Y} = \underline{T} \underline{Q}^* + \underline{Y} \quad (\text{All vectors are row vectors; } \underline{I} \text{ is a row vector of ones.})$$

Inflow analysis:

$$T_i = f_{ij} + z_i = q_{ij}^{**} T_j + z_i$$

$$T_j = f_{ji} + z_j = q_{ji}^{**} T_i + z_j$$

$$\underline{T} = \underline{F} \underline{I} + \underline{Z} = \underline{Q}^{**} \underline{T} + \underline{Z} \quad (\text{All vectors are column vectors; } \underline{I} \text{ is a column vector of ones.})$$

Figure II-1. Simplified two-compartment model to illustrate definitions of terms. (Terms are defined in the text.) Specific inputs, outputs, and intercompartmental flows used in inflow and outflow analyses are illustrated.

Substituting Eq. II-2 into Eq. II-1, converting to matrix notation, and solving for \underline{T} yields:

$$\underline{T} = \underline{Y} (\underline{I} - \underline{Q}^*)^{-1} \quad (\text{II-3})$$

where \underline{T} and \underline{Y} are row vectors and \underline{I} is the identity matrix.

Complete derivations are presented in Appendix C.

We can substitute \underline{N}^* for $(\underline{I} - \underline{Q}^*)^{-1}$:

$$\underline{T} = \underline{Y} \underline{N}^* \quad (\text{II-4})$$

The elements n_{ij}^* of \underline{N}^* define the structure of the system. It is possible to vary \underline{T} to change output \underline{Y} without varying \underline{N}^* . The element n_{ij}^* can be considered the amount of flow through compartment j due to a unit of flow ending in compartment i , or leaving the system from compartment i . Stated another way, n_{ij}^* is the proportion of outflow from j that has already passed through compartment i . The \underline{N}^* matrix thus embodies all the interdependencies among the compartments due both to direct and indirect (recycled) flows.

For a steady-state system the throughflow for compartment k can also be defined as the internal consumption plus inputs:

$$T_i = \sum_{j=1}^n f_{ij} + z_i \quad (\text{II-5})$$

where

z_i = input from the environment to i

If the nutrient flow out of a compartment is proportional to the throughflow of that compartment then:

$$f_{ij} = q_{ij}^{**} T_j \quad (\text{II-6})$$

where

q_{ij}^{**} = an element of matrix \underline{Q}^{**} representing the portion of the throughflow of i that comes from j .

As was done for Q^* , the equation is solved, becoming:

$$\underline{T} = \underline{N}^{**} \underline{Z} \quad (\text{II-7})$$

where

each n_{ij}^{**} element of \underline{N}^{**} is the amount of flow in compartment i due to a unit of flow starting in j , or entering j from the environment (Fig. II-1).

Nutrient flow in the ecosystem can be viewed from the perspective of outflows (Eq. II-4) when one is interested in the original sources of the nutrient forms that feed into the internal cycling pathways of the system, and that eventually contribute to compartment outflows. For example, this perspective of phosphorus cycling could be used to define the relative outflows of all phosphorus forms into the Chesapeake Bay due to a particular source in the watershed. Conversely, when one is concerned with the internal pathways and ultimate fate of nutrient forms entering the system, an inflow analysis (Eq. II-7) may be appropriate. This perspective is valuable for analysis of the DO problem in the reservoirs. Concerns about the reservoirs center on the relative contributions of different phosphorus sources to metabolic rates.

B. FLOW INDICES

A number of indices derived from flow analysis provide useful information about system functions (Finn 1980). Total system throughflow (TST), the sum of the throughflows of all compartments, is a measure of the activity of the whole system:

$$\text{TST} = \sum_{k=1}^n T_k \quad (\text{II-8})$$

For phosphorus, the TST value may be a good indicator of total metabolic activity, which may in turn be proportional to oxygen consumption.

For a system in steady state, the average path length, \overline{PL} (TST divided by either the sum of the inflows or sum of the outflows), describes the average number of compartments a unit of material visits while in the system:

$$\overline{PL} = \frac{\text{TST}}{\sum_k z_k} = \frac{\text{TST}}{\sum_k y_k} \quad (\text{II-9})$$

The more compartments a unit of phosphorus visits during passage through the ecosystem, the more likely it is to be involved in metabolism.

The portion of total throughflow that has gone through at least one complete cycle (i.e., has returned to the original compartment by any path) is defined as TST_C .

$$TST_C = \sum_{k=1}^n \left(\frac{n_{kk}^* - 1}{n_{kk}^*} \right) T_k \quad (II-10)$$

where

n_{kk}^* = the k th diagonal element of \underline{N}^* (i.e., the amount of flow in compartment k generated by a unit of flow starting in compartment k).

Straight-through system throughflow (TST_S) represents the difference between total system throughflow and cycled throughflow, i.e., throughflow that has never passed through a complete cycle:

$$TST_S = TST - TST_C \quad (II-11)$$

The fraction of phosphorus that passes through a cycle (i.e., travels over the same pathway more than once) may be an indicator of that portion of phosphorus catalyzing more DO consumption than if unidirectional paths through the system were taken. In other words, a unit of cycled phosphorus will be metabolized more than once, while a unit of phosphorus passing through the ecosystem without cycling will interact with oxygen only once.

Similarly, straight-through path length is defined as:

$$PL_S = \frac{TST_S}{\sum_k z_k} = \frac{TST_S}{\sum_k y_k} \quad (II-12)$$

The cycling index (CI), a measure of the fraction of TST that has been recycled, is defined as:

$$CI = TST_C / TST \quad (II-13)$$

The cycling index normalizes the amount of phosphorus cycled to the total amount of phosphorus throughflow. The CI thus permits a comparison of the relative amounts of cycled phosphorus among ecosystems of different complexities. Finn's (1980) cycling index (CI) has been criticized on theoretical

grounds (Richey et al. 1982, Patten and Higashi 1984). Richey et al. (1982) proposed several alternative flow indices measuring direct, indirect and recycled flows. Empirical tests indicated that Finn's CI produced values comparable to their indirect index, but with dynamic patterns similar to their cycled flow index. This suggested that CI included both cycled and indirect flow components.

The purpose of the use of CI for this study is a comparison of the relative amounts of phosphorus cycling in Conowingo Reservoir vs. those cycling in the four reservoir system. The evidence indicates that CI or the alternatives would produce similar results. CI was chosen for use because of the large number of previous studies for which CI values are available for comparison.

The derivations presented in Eqs. II-1 to II-13 were simplified in that the systems were assumed to be at steady state. For systems where one or more compartments are not at steady state, the equations for compartmental throughflow, T_k (Eqs. II-1 and II-6), must be modified to include increases or decreases in the material pools of the compartments. Increases in storage are treated as outflows, and decreases in storage are treated as inflows. These derivations are fully described by Finn (1977, 1980) and will not be reproduced here. In the analyses of this report, some of the models treat compartments as being at steady state, while other models allow compartments to increase or decrease in response to the relative amounts of inflowing and outflowing phosphorus. The type of model used for particular analyses of this study depended mostly on data availability (the detailed specifications of the models used here are presented later in Table II-4).

C. APPLICATION OF FLOW ANALYSIS TO THE CONOWINGO RESERVOIR ECOSYSTEM

The first application of flow analysis attempts to relate phosphorus cycling in Conowingo Reservoir to its DO levels. The historical Conowingo data (Robbins and Mathur 1974; PECO unpublished) permit the estimation of phosphorus flow among a number of compartments (i.e., forms of phosphorus) for different time intervals in the long period of record (1969-1981). Subsequently, inferences from the Conowingo flow analyses on phosphorus-DO relationships can perhaps be extended to combined analyses of phosphorus flow through Conowingo and the three upstream reservoirs. (No DO data are available for the three upstream reservoirs for this time interval.)

The form of the phosphorus flow equations developed for Conowingo is directly applicable to the upstream reservoirs. Accordingly, the methods used for the Conowingo flow analyses, presented below, were also used in the formulation of unified flow models for the four-reservoir system. Thus, the methods sections for these models discuss only the relevant data and differences from the methods used for Conowingo flow analyses.

The data used for Conowingo flow analyses were derived from an extensive monitoring program conducted for the Peach Bottom Atomic Power Station on the reservoir, between 1967 and 1981 (Robbins and Mathur 1974; PECO unpublished). The data consist of biweekly profiles of a number of water quality variables at the inflow (Holtwood Dam discharge), outflow (Conowingo Dam discharge), and at a number of internal stations. For flow analyses of phosphorus, five variables are of concern (total dissolved phosphorus, total suspended solids or seston, phytoplankton chlorophyll, zooplankton density, and phosphorus profiles in the sediments).

These five variables permit the construction of a simple conceptual model for phosphorus flow within the ecosystem (Fig. II-2). Complex phosphorus models can contain 9 or more compartments (e.g., Richey 1977), but the Conowingo data are not sufficient to permit the definition of more than the 5 compartments.

By using literature values for specific weights of zooplankters, nutrient ratios of phytoplankton and zooplankton, and other needed conversion factors (tabulated in reviews and other aquatic models: Jorgensen 1979; Zison et al. 1978; Kremer and Nixon 1978), it is possible to estimate the inflows, outflows, and internal pools for each phosphorus compartment for each of the biweekly sampling dates over the 12-year sampling program.

Inputs and outputs of forms of phosphorus in the reservoir can be estimated by knowing the discharges of the dams and reservoir phosphorus concentrations. (Detailed methods are presented in the next section.) However, the intercompartmental flows (F) were not directly measured. As an alternative to direct flow estimation, the rates of change of phosphorus in the 5 compartments (based on differences over the 2-week sampling intervals) were used to calculate the unknown flows. The Conowingo analyses thus relax the assumption that the phosphorus compartments are at steady state.

However, as Fig. II-2 shows, there are 10 unknown flows to be estimated from changes in only 5 variables. To solve this system of 10 unknown flows in five equations for compartmental rates of change, it was necessary to fix 5 of the 10 unknown flows (i.e., to reduce the problem to 5 unknowns in 5 equations).

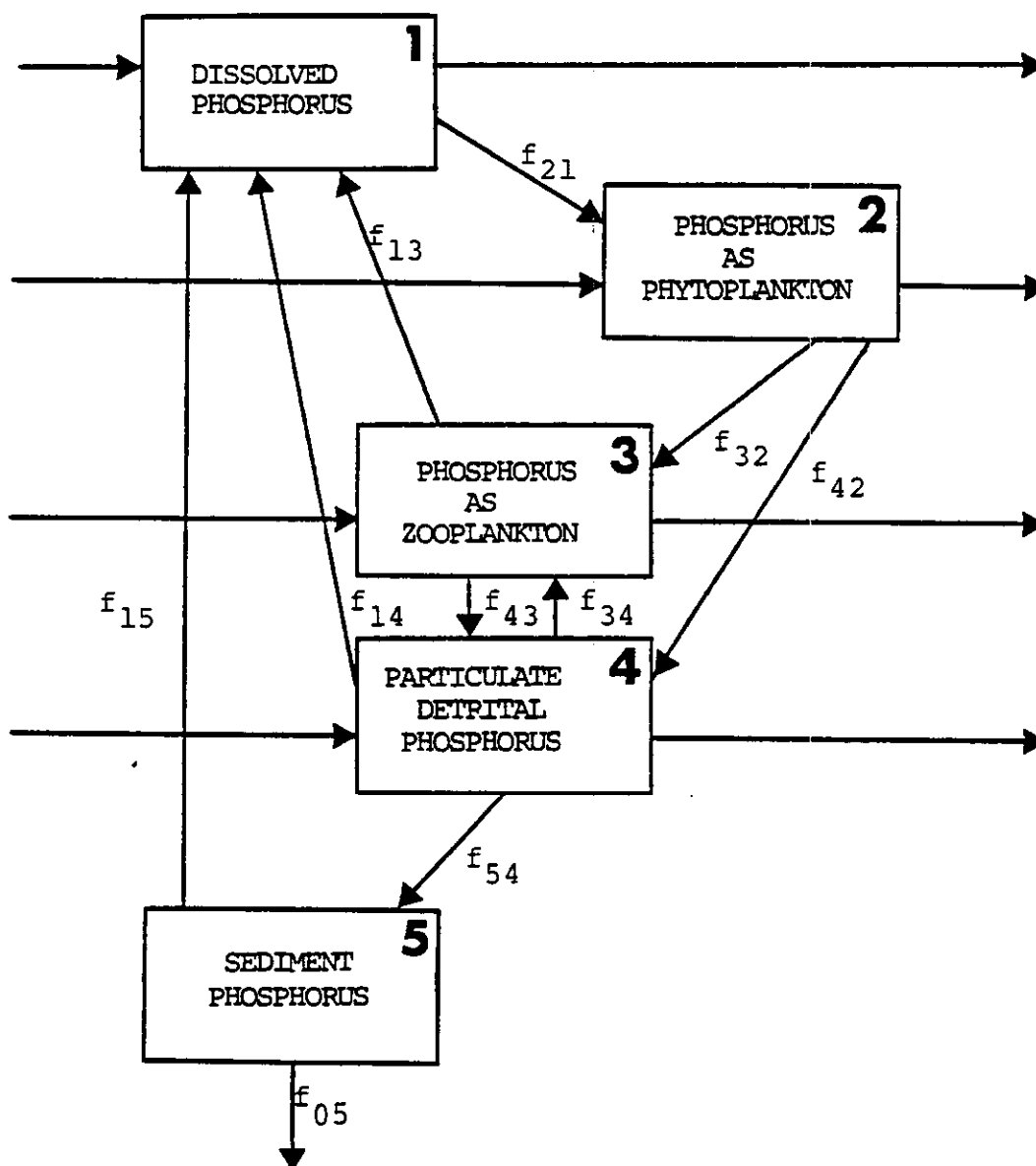


Figure II-2. Five compartment model of phosphorus flow in Conowingo Reservoir

Based on the literature on phosphorus cycling processes and on phosphorus levels in some compartments in Conowingo Reservoir, some of the flows were expected to be relatively small and unimportant. Misestimation of unimportant flows (i.e., by fixing them at arbitrary, but realistic, values) would thus be unlikely to greatly affect estimates of phosphorus throughflow and cycling in the ecosystem. For instance, zooplankton biomass data in the historical Conowingo records indicate very low concentrations relative to other lakes. Because many metabolic phosphorus flows can be considered first-order rate processes (e.g., the total phosphorus flow depends on the total biomass of zooplankton), each of the four intercompartmental flows affecting zooplankton will be small if the zooplankton pool is small.

Other phosphorus flows can be fixed if the rates are known to follow well-documented relationships to other variables (e.g., the exponential relationship between respiration or excretion and water temperature).

The general approach employed for the flow analyses of the Conowingo Reservoir ecosystem was to select 5 of the 10 pathways, and to calculate phosphorus flows for these pathways based on common relationships whose coefficients were derived from the literature. The five remaining flows of the F matrix were derived by the simultaneous solution of the five rate-of-change equations.

Phosphorus Flow Equations

The observed rate of change of dissolved phosphorus (or any other variable) between sampling dates is actually the intrinsic rate of change plus phosphorus input minus phosphorus output. Rearranging terms, the intrinsic rate of change is:

$$\frac{\Delta P_i}{\Delta t} \text{ (intrinsic)} = \frac{\Delta P_i}{\Delta t} \text{ (observed)} - \text{input}_i + \text{output}_i \quad (\text{II-14})$$

where

$$\frac{\Delta P_i}{\Delta t} \text{ (intrinsic)} = \text{the rate of change of concentration in compartment } i, \text{ due to imbalances in intercompartmental flows involving compartment } i$$

$$\frac{\Delta P_i}{\Delta t} \text{ (observed)} = [P(t+1) - P(t)] / [(t+1) - t]$$

(the change in phosphorus concentration
between times t and t+1).

The specific equations for the intrinsic rates of change of each compartment are described below. All fluxes (f_{ij}) are presented here as $\mu\text{g P/l-day}$. They were actually derived (see below) from extensive measurements of the whole reservoir, covering several days or weeks.

Dissolved Phosphorus (Compartment 1)

The dissolved phosphorus pool is depleted by phytoplankton production, and is increased by regeneration from zooplankton, particulate detritus, and the sediments:

$$\frac{\Delta P_1}{\Delta t} \text{ (intrinsic)} = f_{13} + f_{14} + f_{15} - f_{21} \quad (\text{II-15})$$

where

f_{13} = zooplankton excretion of phosphorus (formulated as an unknown flow to be solved for)

f_{14} = remineralization of phosphorus due to bacterial decomposition of particulate organic matter

$$= k_{14} e^{\left(\frac{1.7 \times \text{bottom temperature}}{10} \right)} \times P_4 \quad (\text{II-15a})$$

where

k_{14} = 0.10556 (calculated by Summers (1985) from data collected between 1971 and 1980 in the reservoir.)

P_4 = phosphorus concentration as particulate organic matter (compartment 4)

(Eq. II-15a from Zison et al. 1978)

f_{15} = regeneration of dissolved P by surface sediments

$$f_{15} = \frac{k_{15} e^{(.13 \times \text{bottom temperature})}}{\text{average reservoir depth (m)}} \quad (\text{II-15b})$$

where

$$k_{15} = 0.9$$

(Eq. II-15b and coefficients from Kremer and Nixon 1978; converted to units of mg P/m³-day)

f_{21} = phytoplankton phosphorus uptake (an unknown flow to be solved for).

Phosphorus as Phytoplankton (Compartment 2)

The phytoplankton phosphorus pool is increased by uptake of dissolved phosphorus, and depleted by zooplankton grazing and by death and sinking of phytoplankton:

$$\frac{\Delta P_2}{\Delta t} \text{ (intrinsic)} = f_{21} - f_{32} - f_{42} \quad (\text{II-16})$$

where

f_{21} = phytoplankton phosphorus uptake (as above)

f_{32} = zooplankton grazing on phytoplankton

$$= k_{32} e^{\left(\frac{(\text{bottom temperature} - 20^\circ\text{C}) \times .7}{10} \right)} \times \text{PHYPPREF} \times P_2 \times P_3 \quad (\text{II-16a})$$

where

$$k_{32} = 0.2 \text{ (from Zison et al. 1978)}$$

PHYPPREF = relative food preference (0-1.0) of zooplankton for phytoplankton

$$= 0.7 \text{ (from Zison et al. 1978)}$$

P_2 = phytoplankton phosphorus

P_3 = zooplankton phosphorus

f_{42} = phytoplankton death and sinking (an unknown flow to be solved for).

Phosphorus as Zooplankton (Compartment 3)

The zooplankton phosphorus pool is increased by grazing of zooplankton on phytoplankton and detritus and is depleted by death, excretion, and egestion:

$$\frac{\Delta P_3}{\Delta t} \text{ (intrinsic)} = f_{32} + f_{34} - f_{13} - f_{43} \quad (\text{II-17})$$

where

f_{32} = zooplankton grazing on phytoplankton (as above)

f_{34} = zooplankton grazing on detritus

$$= k_{34} e^{\left(\frac{\text{bottom temperature} - 20^\circ\text{C} \times .7}{10} \right)} \times (1 - \text{PHYPPREF}) \times P_4 \times P_3 \quad (\text{II-17a})$$

where

$$k_{34} = 0.2$$

(Eq. II-17a and coefficients from Zison et al. 1978)

$$f_{43} = k_{43} \times P_3 + (1 - \text{ASSIMEFF}) \times (f_{32} + f_{34}) \quad (\text{II-17b})$$

where

$$k_{43} = .005 \text{ and}$$

ASSIMEFF = assimilation efficiency

$$= .8 \left(\frac{.2}{P_2 + P_4 + .2} \right) \quad (\text{II-17c})$$

(Eqs. II-17b and II-17c, and coefficients, from Zison et al. 1978).

Phosphorus as Particulate Organic Matter (Compartment 4)

The particulate detrital phosphorus pool is increased by death and egestion of zooplankton, death and sinking of phytoplankton, and is depleted by zooplankton grazing on detritus and sinking to bottom sediments:

$$\frac{\Delta P_4}{\Delta t} \text{ (intrinsic} = f_{43} + f_{42} - f_{34} - f_{54}) \quad (\text{II-18})$$

where

f_{43} = zooplankton death and egestion (as above)

f_{42} = phytoplankton death and sinking (as above)

f_{34} = zooplankton grazing on detritus (as above)

f_{54} = settling of detritus to the bottom sediments
(an unknown flow to be solved for).

Phosphorus in Surface Sediments (Compartment 5)

The following processes are assumed to affect the mass balance of phosphorus in the sediments. First, phosphorus is deposited on the surface of the sediments as organic detritus (e.g., dead phytoplankton, organic matter from upstream). Some of this newly deposited material undergoes decomposition and, in the process, phosphorus is remineralized. This phosphorus is added to the dissolved phosphorus pool in the water column. The remaining particulate organic phosphorus is quickly buried by more settled material, and thereafter does not exchange phosphorus with the water column. In other words, there is a thin surface layer that releases phosphorus until the layer is buried by newer material.

These assumptions are supported by the observation that 25-cm sediment cores from Conowingo Reservoir show little change in phosphorus with depth (Sanders et. al. 1982a). It is generally assumed that concentrations in the labile surface layer are not accurately measured because of disturbances during sampling; thus the surface layer is not represented in nutrient profiles from those cores. The large deposition rates in Conowingo Reservoir apparently act rapidly to remove much of the settled phosphorus from biological activity. It is also assumed that the resuspension due to turbulence of particulate organic phosphorus has no net effect on this mass balance, as discussed in Chapter III.

The mass balance for phosphorus in the labile surface layer is thus:

$$\frac{\Delta P_5}{\Delta t} \text{ (intrinsic)} = f_{54} - f_{15} - f_{05} = 0 \quad (\text{II-19})$$

where

f_{54} = settling of detrital material to the sediments
(as above)

f_{15} = regeneration of dissolved phosphorus by the
surface sediments (as above)

f_{05} = permanent burial of phosphorus (an unknown flow
to be solved for).

Solution of Unknown Flows

Once the forced flows are calculated, the five equations become:

$$\frac{\Delta P_1}{\Delta t} = f_{13} - f_{21} - \text{forced flows} \quad (\text{II-20})$$

$$\frac{\Delta P_2}{\Delta t} = f_{21} - f_{42} - \text{forced flows} \quad (\text{II-21})$$

$$\frac{\Delta P_3}{\Delta t} = -f_{13} + \text{forced flows} \quad (\text{II-22})$$

$$\frac{\Delta P_4}{\Delta t} = f_{42} - f_{54} - \text{forced flows} \quad (\text{II-23})$$

$$\frac{\Delta P_5}{\Delta t} = f_{54} - f_{05} - \text{forced flows} \quad (\text{II-24})$$

Four of the five unknown flows (f_{21} , f_{42} , f_{54} , f_{05}) represent the major pathway of phosphorus through the system: dissolved P to phytoplankton, phytoplankton to detritus, detritus to the surface sediments, and finally, long-term burial. The five other flows were selected for forcing for two reasons. Their values were expected to be small, and the rates could be calculated using data from the literature. This selection of

forced and unknown flows is discussed in Chapter III. In matrix notation the five equations become:

$$\begin{bmatrix} \frac{\Delta P_1}{\Delta t} \\ \frac{\Delta P_2}{\Delta t} \\ \frac{\Delta P_3}{\Delta t} \\ \frac{\Delta P_4}{\Delta t} \\ \frac{\Delta P_5}{\Delta t} \end{bmatrix} - \begin{bmatrix} \text{forced} \\ \text{flow} \\ \text{terms} \end{bmatrix} = \begin{bmatrix} 1 & -1 & 0 & 0 & 0 \\ 0 & 1 & -1 & 0 & 0 \\ -1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & -1 & 0 \\ 0 & 0 & 0 & 1 & -1 \end{bmatrix} \begin{bmatrix} f_{13} \\ f_{21} \\ f_{42} \\ f_{54} \\ f_{05} \end{bmatrix} \quad (\text{II-25})$$

or,

$$\frac{\Delta P}{\Delta t} - \text{forced flows} = \underline{A} \underline{K} \quad (\text{II-26})$$

$$\underline{\underline{\frac{\Delta P}{\Delta t}}} \text{ (corrected)} = \underline{A} \underline{K} \quad (\text{II-27})$$

Solving for \underline{K} by premultiplying both sides by \underline{A}^{-1} :

$$\underline{A}^{-1} \underline{\underline{\frac{\Delta P}{\Delta t}}} \text{ (corrected)} = \underline{K} \quad (\text{II-28})$$

This procedure (Eqs. II-14 to II-28) was applied to the data for each sampling interval between 1968 and 1981. Missing data for one or more constituents, or high river flows (that would have completely flushed out the reservoir between the biweekly samples), forced the deletion of data for many time intervals; a total of 79 useful biweekly periods remained for which flow analyses could be performed.

Estimation of Inputs and Outputs of Phosphorus for Conowingo Reservoir

Fluxes of each form of phosphorus into and out of the reservoir were calculated as concentration times water flow. The large water volume of Conowingo Reservoir, and the extensive time-series data for both water flow and the constituents, suggested that the input and output estimates used for a flow analysis for a time interval should be staggered by the water residence time corresponding to the river flow for the period. This is a first-order attempt to follow each mass of water as it travels downstream in the long narrow reservoir. The details of the method used to lag the outputs after the inputs of phosphorus are presented in Appendix C. The lags of outputs after inputs generally were 2-3 weeks under summertime river flow conditions.

D. APPLICATION OF FLOW ANALYSIS TO PHOSPHORUS CYCLING IN THE FOUR-RESERVOIR SYSTEM

Introduction

The amounts of particulate and dissolved phosphorus entering Conowingo Reservoir are dependent on all the processes of the three upstream reservoirs. Thus, this whole river reach should be viewed from a unified system perspective; the functioning of each reservoir should not be examined separately.

An assessment of phosphorus transport and cycling in all four reservoirs requires simultaneous data on the phosphorus inputs and fluxes everywhere in the system. However, synoptic data collection in all reservoirs was done only three times. The first was a set of intensive surveys in Safe Harbor and Holtwood Reservoir in August 1981 conducted by Roy F. Weston, Inc. (1982, 1983), accompanied by intensive surveys in Conowingo Reservoir conducted by CBL (Sanders et al. 1982a), Environmental Resource Management (ERM) (Potera et al. 1982), and Radiation Management Corp. (unpublished). The second and third instances of synoptic data collection were surveys conducted by CBL under subcontract to Martin Marietta to assess seston and nutrient dynamics in all four reservoirs in September-October 1983, and in June 1984 (Appendix A). Although both the 1981 intensive study and the CBL seston study included measurements of inputs from upstream of the reservoirs, inputs from sewage treatment plants and from a number of major tributaries were incompletely sampled. These data had to be supplemented with data from a number of studies that measured

constituents during other periods. The following two subsections describe the methods used to estimate inputs and intercompartmental flows for the 1981 and CBL studies--the second and third of the three sets of analyses presented in this report.

As discussed briefly in Section I.B, the CBL data also permitted the validation of some of the unknown phosphorus flows that had to be estimated for the Conowingo flow analyses. The results of that validation are presented with the CBL analyses.

1981 Intensive Surveys

Data sources for generating phosphorus inputs and intercompartmental flows are summarized in Table II-1. No data on intercompartmental flows were available for York Haven Reservoir. Accordingly, the upstream boundary for this analysis was relocated to the Wrightsville transect at the headwaters of the Safe Harbor Reservoir. Data on zooplankton abundance were available only for Conowingo, so four compartments, instead of five, were used to formulate the phosphorus flows in Safe Harbor and Holtwood Reservoirs. Relatively small zooplankton biomasses in Conowingo are probably typical for the other two reservoirs, so the affect of this aggregation is not likely to be important. The resulting 13-compartment flow model is presented in Figure II-3. The figure also names the tributaries for which input data were available. If no tributary data for August 1981 were available, then 1979 or 1980 data (Susquehanna River Basin Commission 1980; U.S. Geological Survey 1981) were used. Roy F. Weston, Inc. (1982, 1983) documented NPDES permit limitations for the major point sources discharging into Safe Harbor and Holtwood Reservoirs. (In this case all are municipal sewage treatment plants.) These data provided information on the last major class of phosphorus inputs to the system.

The intensive surveys in Safe Harbor, Holtwood, and Conowingo Reservoirs were timed so that the surveys generally sampled the same water mass traveling downstream. Times and locations of the intensive surveys are shown in Table II-2; also noted are the survey data used to generate intercompartmental flows and inputs for the August 1981 flow analysis model.

In general, the same methods were used to calculate intercompartmental flows for each of the three reservoirs as were used to estimate unknown Conowingo flows. Specifically, changes in compartment storages over time (i.e., differences between successive samplings during intensive surveys) were corrected for inflows and outflows (see Eq. II-14). Measurements of some intercompartmental fluxes (e.g., photosynthetic production, community respiration), and estimates from the literature of

Table II-1. Data sources for flow analysis of phosphorus in Safe Harbor, Holtwood, and Conowingo Reservoirs; August 1981.

Reservoir	Station Location(s)	Dates	Constituents sampled	Institution	Sponsor	Reference
Safe Harbor	Harrisburg	1 Apr 1980 - 31 Mar 1981	All water quality constituents, river flow, sediment load	Harrisburg Area Office, USGS	Ches. Bay Prog., U.S. EPA	Fishel (1984)
	Harrisburg	1 Oct 1980 - 1 Sep 1981	All water quality constituents, river flow, sediment load	Harrisburg Area Office, USGS	---	---
	Paxton, Yellow Breeches, Swatara, Conowingo, Codorus, and Chickies Creeks	1 Jul 1980 - 9 Sep 1980	Stream flow, BOD, all forms of N and P	SRRC	---	---
	York Haven (Brunner I, SES)	1981 - 1983 (monthly)	Major inorganic forms	PP&L	---	Skinner (1983)
	River south of York Haven	-	Water travel times from York Haven to headwaters of Safe Harbor Res.	Sutron, Inc.	GPU	Sutron Corporation (1982)
	River south of York Haven	1981 - 1982	NPDES permit limitations for P, BOD, total suspended solids	Roy F. Weston, Inc.	BGE and PP&L	Roy F. Weston, Inc. (1982, 1983)
	Chickies and Codorus Creeks	1-2 Aug 1981 First Intensive 17-18 Aug 1981 Second Intensive	Stream flow, BOD, all forms of N and P	Roy F. Weston, Inc.	BGE and PP&L	Roy F. Weston, Inc. (1982, 1983)
	14 transects between York Haven & Safe Harbor Dams	Intensive surveys: 1-2 Aug 1981 17-18 Aug 1981	All water quality parameters, water column productivity and respiration, benthic respiration	Roy F. Weston, Inc.	BGE and PP&L	Roy F. Weston, Inc. (1982, 1983)
	8 of the transects	Seasonal samplings: 30 May - 13 Oct 1981	DO, temperature	Roy F. Weston, Inc.	BGE and PP&L	Roy F. Weston, Inc. (1982, 1983)

Table II-1. Continued

Reservoir	Station Location(s)	Dates	Constituents sampled	Institution	Sponsor	Reference
Holtwood	9 transects between Safe Harbor and Holtwood Dams	Intensive surveys: 6-7 Aug 1981 20-21 Aug 1981	All water quality parameters, water column productivity and respiration, benthic respiration	Roy F. Weston, Inc.	B&E and PP&L	Roy F. Weston, Inc. (1982, 1983)
	5 of the transects	Seasonal samplings: 31 May - 14 Oct 1981	DO, temperature	Roy F. Weston, Inc.	B&E and PP&L	Roy F. Weston, Inc. (1982, 1983)
	Conestoga and Pequea Creeks	During intensive surveys (above)	Stream flow, BOD, all forms of N and P	Roy F. Weston, Inc.	B&E and PP&L	Roy F. Weston, Inc. (1982, 1983)
	Conestoga and Pequea Creeks	1 Jul 1980 - 9 Sep 1980	Stream flow, BOD, all forms of N and P	SRBC	---	---
Conowingo	Pequea Creek	1 Oct 1979 - 27 May 1981	Stream flow, BOD, all forms of N and P	USGS	Ches. Bay Prog., U.S. EPA	USGS (1981) Fishel (1984)
	3 transects between Mason-Dixon Line and Conowingo Dam	Intensive Surveys: 21-23 Jun 1981 9-12 Aug 1981 23-26 Aug 1981 30 Aug 1981 - 2 Sep 1981	Stream flow, BOD, all forms of N and P DO, temperature, BOD major forms of N and P	BMC	PECO	---
	1 of the transects	All 4 intensive surveys	Water column production and respiration, benthic respiration, chlorophyll, total organic carbon	ANSP and CBL	PECO	Sanders et al. (1982a)
	1 of the transects	26 Aug 1981	Sediment profiles of C, N, P	ANSP and CBL	PECO	Sanders et al. (1982a)
Conowingo discharge	All 3 transects	All 4 intensive surveys	Nutrient and DO profiles	ERM and Martin Marietta	PPSP	Potera et al. (1982)
	Conowingo discharge	1978 - Nov 1981	Stream flow and all water quality constituents	USGS	Ches. Bay Prog., U.S. EPA	Lang (1982)
	Holtwood discharge	Aug 1981	Stream flow and all water quality constituents	Roy F. Weston, Inc.	PP&L and B&E	Roy F. Weston, Inc. (1982, 1983)
	Conowingo and Muddy Creeks	1 Jul 1980 - 9 Sep 1980	Stream flow and all water quality constituents	SRBC	---	---

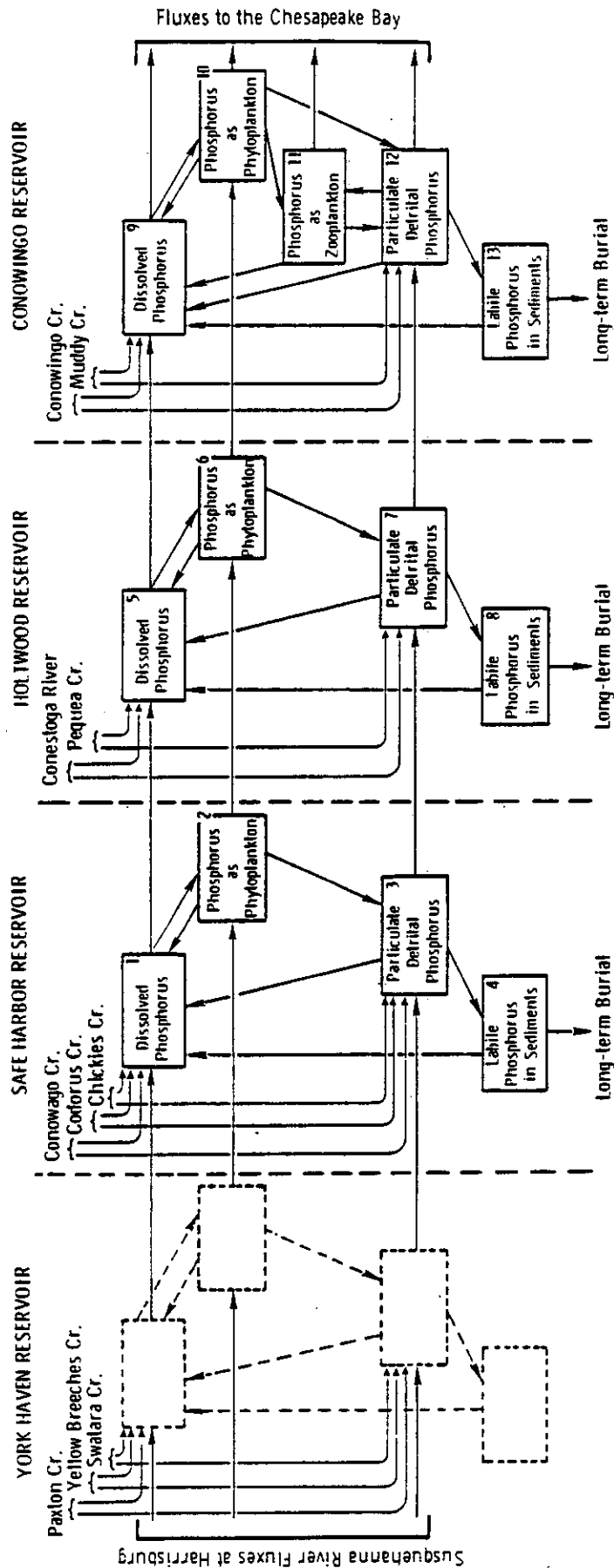


Figure II-3. Thirteen compartment model of phosphorus cycling in Safe Harbor, Holtwood, and Conowingo Reservoirs